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TREATMENT OF WATER FROM CONTAMINATED WELLS

by

Walter A. Feige
Robert M. Clark
Benjamin W. Lykins, Jr.
Carol Ann Fronk

DRINKING WATER RESEARCH DIVISION
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
26 W. ST. CLAIR STREET
CINCINNATI, OHIO 45268

WATER ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OH 45268

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The recently enacted Safe Drinking Water Act Amendments dictates the regulation of 83 contaminants within the next three years and at least 25 more by 1991. For several years, EPA's Drinking Water Research Division (DWRD) has been conducting extensive research into the development of treatment technologies for removing organic and inorganic contaminants from groundwater. This paper describes the status of DWRD's research activities and provides a state-ofthe-art summary of removal techniques. DWRD's research activities are categorized as pilot-, bench-, and fieldscale studies. Carbon adsorption is effective for removing both VOCs and SOCs. Packed tower and diffused aeration are best suited for removing VOCs. Ion exchange has been field-tested to show effective removal of nitrates and pilot-tested for uranium removal. Reverse osmosis (RO) has proven to be effective in the field for radium removal and pilot-tested for nitrate removal. Of the technologies that show promise and are being tested at the bench- and pilot-scales, conventional treatment with powdered activated carbon is effective for removing a few of the SOCs, ozone oxidation is effective for removing certain classes of volatile organic chemicals and SOCs, and certain reverse osmosis membranes and ultraviolet treatment are also potentially effective against VOCs and SOCs. Aeration and carbon adsorption are being examined for their radon removal capabilities.

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ABSTRACT

Groundwater contamination of water supplies in the United States has increased dramatically the past several years. Recently, the U.S. EPA proposed maximum contaminant levels (MCLs) for volatile organic contaminants (VOCs) frequently found in groundwater supplies. In addition, the Agency is planning to propose MCLs for synthetic organic chemicals (SOCs), inorganic chemicals, and radionuclides, all of which have appeared in ground water supplies. The recently enacted Safe Drinking Water Act Amendments dictates the regulation of 83 contaminants within the next three years and at least 25 more by 1991. For several years, EPA's Drinking Water Research Division (DWRD) has been conducting extensive research into the development of treatment technologies for removing organic and inorganic contaminants from groundwater. This paper describes the status of DWRD's research activities and provides a state-of-the-art summary of removal techniques. DWRD's research activities are categorized as pilot-, bench-, and field-scale studies. Carbon adsorption is effective for removing both VOCs and SOCs. Packed tower and diffused aeration are best suited for removing VOCs. Ion exchange has been field-tested to show effective removal of nitrates and pilot-tested for uranium removal. Reverse osmosis (RO) has proven to be effective in the field for radium removal and pilot-tested for nitrate removal. Of the technologies that show promise and are being tested at the bench- and pilot-scales, conventional treatment with powdered activated carbon is effective for removing a few of the SOCs, ozone oxidation is effective for removing certain classes of volatile organic chemicals and SOCs, and certain reverse osmosis membranes

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This is an abstract of a proposed presentation and does not necessarily reflect EPA policy.

KEY WORDS: DRINKING WATER RESEARCH, TREATMENT TECHNOLOGY, CARBON ADSORPTION, AERATION, REVERSE OSMOSIS, ION EXCHANGE, VOCs, SOCs, NITRATES, RADIONUCLIDES

TREATMENT OF WATER FROM CONTAMINATED WELLS

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INTRODUCTION

Groundwater is a natural resource of enormous value. Three-quarters of U.S. cities get their water supplies totally or in part from groundwater and more than half of all Americans rely on it for drinking water. Ninety percent of rural households have no source other than groundwater for drinking water supplies.

A number of recent studies have documented the actual or potential contamination of our nation's groundwater on a wide scale. A survey conducted by the U.S. Environmental Protection Agency (EPA) has documented that 22 percent of approximately 466 randomly sampled utilities produced drinking water containing volatile organic chemicals (VOCs) at detectable levels (Westrick et al. 1984). Other individual studies have shown the presence of pesticides in groundwater, and in recent years concern has been growing over contamination of groundwater by agricultural chemicals (fertilizers, insecticides, nematocides, and fungicides). The concern is greater, of course, when specific chemicals are identified in homeowners' drinking water wells.

Though concern in the past 5 years has centered on VOC contamination of groundwater, several examples illustrate the growing concern over

pesticides. During the last 8 years, New York's Suffolk County Health Department has examined the groundwater underlying Long Island for agricultural organic constituents and their decay products (Lykins et al. 1985). During the testing, 101 agricultural/organic compounds were evaluated, with 41 found in the groundwater. Many of these identified contaminants were present in trace quantities, but aldicarb, carbofuran, 1,2-dichloropropane, and 1,2,3-trichloropropane were at elevated levels. In addition, nitrates from fertilizer applications were present in quantities exceeding the primary drinking water standards. A 1983 study, conducted by the California Department of Food and Agriculture (1983), stated that dibromochloropropane (DBCP), ethylene dibromide (EDB), and simazine were found in San Joaquin Valley wells (Litwin et al. 1983). A report submitted to the California State Water Resources Board states that more than 2000 wells statewide have been found to be contaminated with DBCP (Litwin et al. 1983).

Work conducted near Tiffin, Ohio by EPA's Drinking Water Research Division (DWRD) has shown periodic high quantities of pesticides in surface waters associated with seasonal runoffs (Baker 1983). Although groundwaters have not been sampled in this area, it is likely that some contamination exists. Unlike surface waters, groundwaters are likely to remain contaminated indefinitely. EPA is now proposing to conduct an extensive groundwater survey for pesticides similar to the earlier VOC survey (Cohen 1985). Also underway and almost completed is the EPA National Inorganic and Radionuclide Survey to develop an occurrence data base for certain of those parameters.

Recently, EPA has proposed maximum contaminant levels (MCLs) for VOCs (Phase I) that are frequently found in groundwater supplies (Fed. Reg. Part III 1985). These MCLs are expected to be in final form in the not too distant future. In addition, EPA is planning to propose MCLs for synthetic organic chemicals (Phase II), inorganic chemicals (Phase II), and radionuclides (Phase III) for contaminants that are also frequently found in groundwater (Fed. Reg. Part IV 1985). Previous experience indicates that these Phase I, II and III regulations will have a significant impact on many water utilities in the United States.

Although the most desirable way of controlling groundwater contamination is to prevent pollution at the source, many aquifers are currently contaminated and provide the cheapest water supply to the communities they serve. Water from these aquifers can be treated to achieve quality levels that equal or exceed those being proposed by the Office of Drinking Water. EPA's Drinking Water Research Division (DWRD) has been conducting extensive research for a number of years into the development of treatment technologies for removing both inorganic and organic contaminants from groundwater in a cost-effective manner. Recently, this effort has emphasized the removal of volatile organic chemicals and synthetic organic chemicals such as pesticides, nitrate removal and radionuclide removal.

DWRD's research activities are categorized as pilot-, bench-, and field-scale studies. Most of the bench- and pilot-scale studies are conducted on an in-house basis, and are designed to examine the feasibility of various technologies before their cost and performance are evaluated in the field. The remainder of our research is performed via cooperative agreements to municipalities and other non-profit institutions.

The purpose of this paper is to discuss the status of DWRD's research activities and to provide a state-of-the-art summary on the removal of organic and inorganic contaminants from groundwater.

DWRD'S RESEARCH ACTIVITIES

DWRD is part of the Water Engineering Research Laboratory of the Office of Environmental Engineering and Technology in EPA's Office of Research and Development. The Division consists of 44 permanent full-time employees and has an annual budget of approximately $5 million. DWRD is responsible for evaluating the various types of technologies that may be feasible for meeting the MCLs promulgated under the Safe Drinking Water Act (PL93-523) and its Amendments. The standard research protocol followed by DWRD is to evaluate unit processes at the bench level, move the process to pilot scale for testing, and if its performance is promising, build a prototype for field evaluation. At all stages, cost and performance are key factors in moving a technology to the next phase. Thus, when a technology is tested on a field scale, cost and performance data are routinely collected.

Table 1 summarizes the treatment technologies that DWRD is evaluating for removal of VOCs, synthetic organic chemicals (SOCs), nitrates, and radionuclides from water supplies. The table indicates carbon adsorption is effective for removing both VOCs and SOCs. Packed tower and diffused aeration are best suited for removing VOCs. Ion exchange has been field-tested to show effective removal of nitrates and pilot-tested for uranium removal. Reverse osmosis (RO) has proven to be effective in the field for radium removal and pilot-tested for nitrate removals. Of

the technologies that show promise and are being tested at the bench- and pilot- scales, conventional treatment with powdered activated carbon (PAC) is effective for removing a few of the SOCs, ozone oxidation is effective for removing certain classes of VOCs and SOCs, and certain reverse osmosis membranes and ultraviolet treatment are also potentially effective against VOCs and SOCs. Aeration and carbon adsorption are being examined for their radon removal capabilities. Each of these technologies is discussed in this paper.

FIELD- AND PILOT-TESTED TECHNOLOGIES

Carbon Adsorption

DWRD has been conducting extensive studies on the use of granular activated carbon (GAC) treatment with onsite regeneration for 10 years. Most of this research has been devoted to demonstrating the effectiveness of GAC for surface water treatment (Lykins et al. 1984). More recently, DWRD has been conducting studies that incorporate the use of carbon treatment for removal of VOCs and SOCs from groundwater. GAC is being studied for removing contaminants from groundwater at Suffolk County, New York, California's San Joaquin Valley, and Wausau, Wisconsin. Each of these projects is designed to examine a different aspect of GAC application and except for Wausau, they are intended to deal with the little-understood pesticide contamination problem.

In Suffolk County, the removal of organics and pesticides, including aldicarb, carbofuran, 1,2-dichloropropane, 1,2,3-trichloropropane, and also nitrates is being studied under various flow situations. Two parallel treatment systems (one consisting of GAC and ion exchange and the other consisting of reverse osmosis) are being operated at low flows

similar to home usage. The costs for these two systems will be established along with unit operating efficiency so that a larger public water supply system can be designed and tested. The results from this study will be applicable to other areas, especially in farming communities, where multiple contamination of groundwater is identified.

The principal objectives of the San Joaquin Valley study are to (1) develop cost-effective design criteria for the removal of dibromochloropropane and other pesticides from water supplies by GAC, and (2) to improve and strengthen existing administrative guidelines and jurisdictional responsibilities pertaining to both community water systems and private wells containing the compounds of interest. Pilot studies are being conducted with GAC, and results will be compared with those from existing operating systems. Minicolumn studies as described below are taking place to predict breakthroughs. The focus in this study will be on point-of-use GAC units that are now in use by small systems, individual homeowners, and farmers in the area. Disposal of treatment residues is also being studied.

The third site, in Wausau, Wisconsin, has multiple contaminants in its groundwater source from a nearby superfund site. GAC is the primary technology being studied, but air-stripping is being examined as a companion technology. The Wausau project is unique in that modeling techniques are being used to predict full-scale design criteria for a GAC plant. These predictions are being evaluated against the actual cost and performance associated with the building of GAC contactors onsite. The results from this study are expected to provide a useful methodology for extension to other GAC applications. The modeling techniques will be particularly useful in studying the long list of SOCs and VOCs that may

be proposed for regulation under the current and future provisions of the Safe Drinking Water Act. In addition to modeling, minicolumn technology is also being studied. This methodology potentially allows investigators to acquire water from a given site and to study the performance of a small, high-pressure column in the presence of a natural water background. Results from these minicolumn experiments are expected to reproduce the breakthrough curve normally seen in pilot- and full-scale facilities.

Packed Tower

Aeration technology has proved to be especially effective for the removal of VOCs. However, the research at Wausau, Wisconsin (which also incorporates air stripping) indicates that aeration may in some cases be effective for removing compounds that have somewhat lower Henry's Law Constants than would normally be expected to be removed by this process (Hand 1986). In this project, as with the carbon facilities, modeling is being used to predict the performance of packed-tower aeration. Air-stripping off-gas studies at Wausau are being conducted in cooperation with the American Water Works Association Research Foundation.

DWRD also has an air-stripping research project currently underway at Baldwin Park, California which is examining the removal of VOCs from a groundwater supply. As in Wausau, the Baldwin Park project is also examining the problems of off-gas control technology.

Two other field-scale activities dealing with air-stripping have been concluded at Brewster and Glen Cove, New York (Wallman and Cummins 1986, Ruggiero and Feige 1984). In the Brewster project, modeling techniques and pilot-scale facilities were used to determine the scale-up relationships to be used for full-scale, air-stripping facilities.

The purpose of the project was to develop a technique that could be used by consulting engineers to adequately predict the cost and performance of full-scale facilities using pilot aeration columns. At Glen Cove, various aeration designs were evaluated for their ability to remove VOCs from drinking water. Packed column, diffused aeration, and induced-air all proved technically feasible to reduce contaminant levels to meet existing state guidelines.

Ion Exchange

Ion exchange technology has been field-tested for nitrate removal under a DWRD-supported cooperative agreement (Lauch and Guter 1986) and has been pilot-tested for uranium (Reid et al. 1985) removal at sites in the western part of the United States.

The nitrate removal plant has been operating automatically for about 3 years. The 1-mgd (0.38 ML/d) demonstration plant is located in McFarland, CA and consists of three anion exchange vessels that are designed to reduce nitrate levels to below 10 mg NO_3-N/L, the EPA MCL and also the California requirement. Currently, about 500 gpm (32 L/S) of water is being treated and about 200 gpm (13 L/S) is bypassed and later blended with the treated water, resulting in a total product flow of 700 gpm (44 L/S). The blended water adequately meets the nitrate MCL and EPA's Secondary Regulation (Fed. Reg. 1979) for chloride and sulfate levels.

Bench-scale studies were initially conducted at EPA-Cincinnati for uranium removal and later pilot-tested (Reid et al. 1985). The laboratory work showed that when drinking water containing 300 ug/L uranium was passed through anion exchange resin, more than 9,000 bed volumes were treated before breakthrough was observed. DWRD then evaluated the performance of twelve 1/4-cubic-foot (0.007 m^3) anion-exchange systems installed

in New Mexico, Colorado, and Arizona at sites where uranium levels in the raw water exceeded 20 ug/L. Results confirmed the findings shown in the laboratory. Because of the high loading capacity of the anion resins for uranium, these units are well suited for point-of-use applications where on-site regeneration is not feasible. For centralized treatment, the resin may be regenerated and recycled by backwashing it with sodium chloride solution.

Reverse Osmosis

Groundwater sources in Illinois, Iowa, Florida, Texas, Wisconsin, and some Rocky Mountain states contain radium in excess of the 5 pCi/L MCL. RO treatment of radium-laden ground water was demonstrated in 1977 when DWRD and Sarasota County, FL water supply staff undertook a cooperative effort to study the operation of eight RO systems (Sorg et al. 1980). The systems were located in small communities serving a population from 39 to 15,000 and the design capacities varied from 800 gpd (3 kL/d) to 1 mgd (3.8 ML/d). Six different manufacturers of RO systems were represented and both the hollow fiber and spiral wound cellulose acetate membranes were used. The study showed from 82-96% Ra-226 removal for all systems, resulting in treated water that contained below the EPA MCL of 5 pCi/L.

RO technology has also been pilot tested for nitrate removal as part of DWRD cooperative agreements at three locations (Lykins and Baier 1985, Huxstep 1981, Guter 1982). As mentioned previously, high nitrate levels exist in the well waters of Suffolk County, LI, NY, along with several SOCs (Lykins and Baier 1985). This combination of organic and inorganic contaminants is the reason that RO was selected as one of the treatment

technologies to be studied there. Seven commercially available membranes were evaluated for their rejection capabilities. Nitrate removals ranged from 75-95%, and research is continuing with one of the polyamide membranes that proved relatively efficient for both nitrate and SOC rejection. At Charlotte Harbor, FL (Huxstep 1981), both high pressure (265-359 psig) and low pressure (163-187 psig) RO systems were studied for the removal of several spiked inorganic contaminants, including nitrate, from a natural groundwater. The investigation showed that the high pressure system was significantly more effective for removing all substances measured. The comparison for nitrate removals, for example, was 80% vs. 6-24%. Before ion exchange was selected for full-scale evaluation at McFarland, CA, a 20,000 gpd (77 m^3/d) RO system was examined for nitrate removal (Guter 1982). Even though the system experienced frequent electrical and mechanical failures, nitrate rejection of about 65% was achieved.

PROMISING TECHNOLOGIES

Conventional Treatment

Conventional treatment is unlikely to be used for treating groundwater. However, field studies are being conducted at Tiffin, Ohio, where the river source contains periodically high concentrations of pesticides because of local agricultural applications. Powdered activated carbon, added to the water normally treated only by conventional treatment, appears to be quite effective for removing synthetic organic chemicals.

Ozone Oxidation

Ozone oxidation was being studied extensively in DWRD's in-house pilot plant facilities (Fronk, date pending). Controlled pilot plant

ozone treatment tests were conducted on 29 VOC's in distilled water and groundwater. Results showed that aromatic compounds, alkenes and certain pesticides are well removed by ozone treatment but that alkanes are poorly removed. Also, removal efficiency improved for the alkenes and aromatic compounds with increasing ozone dosage and for some alkanes with increasing pH. For most compounds, the efficacy of ozone was not affected by the background water matrix. Information from the literature concerning the ozone treatment of pure materials in the gaseous or liquid phase generally predicted the effectiveness of ozone in treating aqueous solutions.

Reverse Osmosis

Reverse osmosis (RO) has shown some promise in removing both VOCs and SOCs from groundwater (Sorg and Love 1984). Most of the efforts by DWRD to date have been on a pilot- or bench-scale basis, with some limited application of reverse osmosis for the removal of organics at the Suffolk County study mentioned previously. Preliminary indications are that certain RO membranes are very effective in removing a wide range of organic chemicals.

Ultraviolet Treatment

Ultraviolet light also shows some promise for removing organic contaminants, particularly when combined with ozone. DWRD has recently awarded a cooperative agreement to the Los Angeles Water and Power Company that deals with the removal of VOCs from groundwater using these two technologies. If successful, these chemicals will be oxidized to CO_2 and water, and the need to deal with off-gas control problems may be eliminated.

Radium Removal Technologies

DWRD has sponsored research to study promising methods for radium removal (Myers et al. 1985, Snyder et al. 1986). The ion exchange process, with both weak acid resin and strong acid resin were investigated. Both resins effectively removed radium from water to well below the 5 pCi/L MCL and, in most cases, to <0.5 pCi/L, respresenting 96% + removal. The weak acid resin in the hydrogen form also removed hardness, which was not the case for the strong acid resin in the calcium form. The maximum capacity of the weak-acid resin was about 2.3 times that of strong acid resin and much less spent regenerate per unit volume of water treated was produced from the weak-acid column than from the strong-acid column. Another part of this project was to determine the feasibility of Dow Chemical Company's Radium-Selective Complexer (RSC)* for removing radium from brines compared with typical groundwaters. The RSC is a synthetic resin that has a high affinity for radium. The capacity of RSC was observed to have been about 200 times greater in 450 mg/L TDS water than in 40,000 mg/L TDS brine (51,000 pCi/dry g vs. 300 pCi/dry g). However, the effect of other parameters, including calcium, sodium, and other ions, in addition to EBCT needs to be determined. The application of the RSC for treatment of radium from brines is presently being studied at a small community in Colorado under a research cooperative agreement with DWRD.

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*Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Radon Removal Technologies

In response to the Agency's recent emphasis on radon in the environment, DWRD has funded a project to evaluate several treatment techniques for the removal of radon from community water supplies. Three treatment methods, packed tower aeration, diffused bubble aeration and granular activated carbon (GAC) will be evaluated for the removal of radon from two community water supplies in New Hampshire. The study will compare the methods for effectiveness, costs, operation, maintenance and other related factors. To accomplish the objectives, the three treatment systems will be constructed and operated at each of the two sites. The two sites selected are trailer parks, one whose water supply serves 40 homes with an average daily flow of 4.6 gpm and an average radon concentration of 155,000 pCi/L. The other location has 56 homes, the average daily water usage is 6.3 gpm, and the average radon concentration is 40,000 pCi/L. After construction of the treatment systems, they will be operated for 6-12 months. At the end of this project, a report will be developed as a guideline to help State Agencies and small communities select an appropriate technology for radon gas treatment in public water supplies.

SECONDARY PROBLEMS

DWRD is very concerned that the technologies studied lead to no secondary problems. For example, while conducting GAC research on surface water supplies, it was discovered that dioxins were formed in the reactivation process. An extensive evaluation lead to the installation of an

afterburner, which was found to eliminate these dioxin byproducts when operating at a temperature of 2400°F (Miller et al. 1986).

At Baldwin Park, California, the use of high-stack dispersion was investigated as a means of minimizing the impact of VOC removal from groundwater. At Baldwin Park and at Wausau, Wisconsin, gas-phase adsorption is being investigated for removal of both VOCs and SOCs from air stripping waste gases.

The project with the Los Angeles Water and Power Company is intended to investigate the water-phase oxidation of VOCs and SOCs to CO_2 and H_2O using ozone in combination with ultraviolet light. Gas-phase oxidation of VOCs and SOCs by ozone and ultraviolet light also appears promising.

Future work will concentrate on residuals control from various unit processes such as reverse osmosis and ion exchange.

COST AND PERFORMANCE

All of the field studies conducted by the DWRD include cost and performance as part of the data gathered for later evaluation and extrapolation to other conditions. In addition, as bench- and pilot-scale studies are conducted, cost estimates based on the development of cost equations and cost curves from previous studies are used to predict the most cost-effective technologies on which to concentrate scarce resources. Table 2 compares the costs and performance calculations for carbon adsorption, tower aeration, and diffused-air aeration for a selected set of VOCs (Clark et al. 1984). Estimated operation, maintenance, and capital costs for reverse osmosis and ion exchange technologies are found in two EPA reports (Gumerman et al. 1979, Gummerman et al. 1985).

Some of the point-of-use technologies discussed in this paper might best be managed by a centralized or circuit rider approach. In this case, the central authority would assume responsiblity for monitoring and maintaining the individual units installed on the homeowner's premises.

SUMMARY AND CONCLUSIONS

DWRD is responsible for evaluating the various types of technologies that might be used to meet the MCLs promulgated under the Safe Drinking Water Act and its Amendments. Because the source water for many utilities in the United States is groundwater, DWRD is especially concerned about conducting bench-, pilot- and field-scale studies on technologies that effectively treat groundwater. Technologies being examined are carbon adsorption, aeration, ion exchange, reverse osmosis, ozone oxidation, and ultraviolet light, some at the field-scale and others at the bench and pilot scales. Table 3 summarizes the various technologies examined for organics removal, and based on data gathered to date, it attempts to characterize their relative performances for both Phase I and Phase II organics. Table 4 is a similar summary for removal of nitrate and radionuclides and shows that ion exchange and reverse osmosis each result in excellent contaminant removals.

Although Table 3 only provides a general guideline for removal of compounds, several interesting trends are noted. Carbon adsorption appears to provide removal for a wide range of organics whereas conventional treatment is revealed as a poor treatment for those compounds listed in the table. Packed tower aeration manifests itself as an

excellent technology for volatile organic compounds and may have application for a limited number of pesticides. Ozone oxidation appears to be a good treatment technology for certain classes of organics such as simple alkenes and aromatics, as well as certain similar, but more complex organic structures. Although only a few organics have been subjected to long-term testing via reverse osmosis, promising removals for several low molecular weight organics can be seen.

Tables 3 and 4 were generated using a variety of sources, including EPA-DWRD pilot- and field-scale studies, Henry's Law Constants for prediction of removal of some of the pesticides, as well as the use of oxidative trends for predicting the removal of complex pesticides. These tables, therefore, carries the caveat that the cited removals should not be used for design purposes, but that each technology must be tested on compounds, under field conditions, before the EPA-DWRD will advocate a technology's use. Given the widespread nature of groundwater contamination, these technological evaluations should be highly useful to EPA's regulatory process and to consultants, state officials, and individual communities as well.

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TABLE 1. TREATMENT TECHNOLOGIES EVALUATED BY DWRD FOR REMOVING VOCs, SOCs, NITRATES, AND RADIONUCLIDES FROM DRINKING WATER

Technology Status	Technology	Contaminant Class or Specific Contaminant Removed
Field-tested	1. Carbon Adsorption	1. VOCs, SOCs
	2. Packed Tower and Diffused-Air Aeration	2. VOCs
	3. Ion Exchange	3. Nitrates
	4. Reverse Osmosis	4. Radium
Pilot-tested	1. Reverse Osmosis	1. Nitrates, Uranium
	2. Ion Exchange	2. Uranium
Promising Technologies	1. Conventional Treatment with Powdered Activated Carbon	1. SOCs
	2. Ozone Oxidation	2. VOCs, SOCs
	3. Reverse Osmosis	3. VOCs, SOCs
	4. Ultraviolet Treatment	4. VOCs, SOCs
	5. Ion Exchange	5. Radium
	6. Selective Complexer	6. Radium
	7. Aeration	7. Radon
	8. Carbon Adsorption	8. Radon

TABLE 3. PERFORMANCE SUMMARY FOR ORGANIC TECHNOLOGIES EXAMINED

Regulatory Phase	Organic Compounds	REMOVAL EFFICIENCY† Granular Activated Carbon Adsorption Filtrasorb 400[a]	Packed Tower Aeration	Reverse Osmosis Thin Film Composite	Ozone Oxidation (2-6 ppm)	Conventional Treatment
VOLATILE ORGANIC CONTAMINANTS						
	Alkanes					
I	Carbon Tetrachloride	++	++	++	0	0
I	1,2-Dichloroethane	++	++	+	0	0
I	1,1,1-Trichloroethane	++	++	++	0	0
II	1,2-Dichloropropane	++	++	++	0	0
II	Ethylene Dibromide	++	++	++	0	0
II	Dibromochloropropane	++	+	NA	0	0
	Alkenes					
I	Vinyl Chloride	++	++	NA	++	0
II	Styrene	NA	NA	NA	++	0
I	1,1-Dichloroethylene	++	++	NA	++	0
II	cis-1,2-Dichloroethylene	++	++	0	++	0
II	trans-1,2-Dichloroethylene	++	++	NA	++	0
I	Trichloroethylene	++	++	++	+	0
	Aromatics					
I	Benzene	++	++	0	++	0
II	Toluene	++	++	NA	++	0
II	Xylenes	++	++	NA	++	0
II	Ethylbenzene	++	++	0	++	0
II	Chlorobenzene	++	++	++	+	0
II	o-Dichlorobenzene	++	++	+	+	0
I	p-Dichlorobenzene	++	++	NA	+	0
PESTICIDES						
II	Pentachlorophenol	++	0	NA	++	NA
II	2,4-D	++	0	NA	+	0
II	Alachlor	++	++	++	++	0
II	Aldicarb	NA	0	NA	NA	NA
II	Carbofuran	++	0	++	++	0
II	Lindane	++	0	NA	0	0
II	Toxaphene	++	++	NA	NA	0
II	Heptachlor	++	++	NA	++	NA
II	Chlordane	++	0	NA	NA	NA
II	2,4,5-TP	++	NA	NA	+	NA
II	Methoxychlor	++	NA	NA	NA	NA

(See footnotes at end of table)

(Continued)

TABLE 3. PERFORMANCE SUMMARY FOR ORGANIC TECHNOLOGIES EXAMINED (Contd.)

Regulatory Phase	Organic Compounds	REMOVAL EFFICIENCY† Granular Activated Carbon Adsorption Filtrasorb 400[a]	Packed Tower Aeration	Reverse Osmosis Thin Film Composite	Ozone Oxidation (2-6 ppm)	Conventional Treatment
	OTHER					
II	Acrylamide	NA	0	NA	NA	NA
II	Epichlorohydrin	NA	0	NA	0	NA
II	PCB's	++	++	NA	NA	NA

†++ = Excellent 70% - 100%
+ = Average Removal 30% - 69%
0 = Poor 0% - 29%
NA = Data not available or compound has not been tested by EPA Drinking Water Research Division
a = Excellent removal category for carbon indicates compound has been demonstrated to be adsorbable onto GAC, in full- or pilot-scale applications, or in the laboratory with characteristics suggesting GAC can be a cost-effective technology.

TABLE 2. COST SUMMARY FOR SELECTED VOCs
(Clark et al. 1984)

VOC	Capacity mgd[+]	Capacity ug/L	Percent removal	Cost, $/thousand gal[†] Tower aeration	Diffused-air aeration	Carbon adsorption
Trichloro-ethylene	0.5	100	90	0.273	0.546	0.868
		10	99	0.287	0.793	0.918
		1	99.9	0.296	1.032	1.010
		0.1	99.99	0.303	1.270	1.124
	1	100	90	0.182	0.383	0.637
		10	99	0.191	0.611	0.679
		1	99.9	0.196	0.850	0.765
		0.1	99.99	0.202	1.088	0.867
	10	100	90	0.083	0.207	0.356
		10	99	0.088	0.403	0.390
		1	99.9	0.093	0.587	0.458
		0.1	99.99	0.099	0.755	0.543
Tetrachloro-ethylene	0.5	100	90	0.279	0.637	0.610
		10	99	0.293	0.935	0.660
		1	99.9	0.302	1.228	0.705
		0.1	99.99	0.308	1.486	0.805
	1	100	90	0.186	0.460	0.453
		10	99	0.194	1.752	0.502
		1	99.9	0.201	1.046	0.548
		0.0	99.99	0.206	1.296	0.651
	10	100	90	0.085	0.277	0.197
		10	99	0.091	0.514	0.224
		1	99.9	0.098	0.726	0.251
		0.1	99.99	0.103	0.905	0.313
1,1,1-Tri-chloro-ethane	0.5	100	90	0.270	0.502	1.445
		10	99	0.289	0.825	1.651
		1	99.9	0.307	1.421	1.945
		0.1	99.99	0.332	2.572	2.605
	1	100	90	0.180	0.348	1.396
		10	99	0.192	0.644	1.500
		1	99.9	0.205	1.234	1.801
		0.1	99.99	0.230	2.313	2.402
	10	100	90	0.082	0.176	0.802
		10	99	0.089	0.430	0.973
		1	99.9	0.102	0.860	1.229
		0.1	99.99	0.122	1.821	1.818
Carbon tetra-chloride	0.5	100	90	0.264	0.428	0.942
		10	99	0.287	0.531	1.021
		1	99.9	0.272	0.600	1.132
		0.1	99.99	0.280	0.648	1.340
	1	100	90	0.176	0.292	0.703
		10	99	0.181	0.371	0.775
		1	99.9	0.184	0.427	0.940
		0.1	99.99	0.186	0.470	1.063
	10	100	90	0.081	0.133	0.408
		10	99	0.083	0.196	0.467
		1	99.9	0.084	0.247	0.550
		0.1	99.99	0.085	0.286	0.719

(See footnotes at end of table)

(Continued)

TABLE 2. COST SUMMARY FOR SELECTED VOCs (Contd.)
(Clark et al. 1984)

VOC	Capacity mgd[+]	Capacity ug/L	Percent removal	Cost, $/thousand gal[†] Tower Aeration	Diffused air aeration	Carbon adsorption
Cis-1,2-Dichloro-ethylene	0.5	100	90	0.284	0.727	2.513
		10	99	0.296	1.010	2.791
		1	99.9	0.304	1.281	3.153
		0.1	99.99	0.310	1.572	3.511
	1	100	90	0.189	0.547	2.156
		10	99	0.196	0.828	2.417
		1	99.9	0.202	1.098	2.760
		0.1	99.99	0.208	1.379	3.099
	10	100	90	0.087	0.350	1.735
		10	99	0.093	0.571	1.989
		1	99.9	0.099	0.763	2.327
		0.1	99.99	0.104	0.966	2.660
1,2-Dichloro-ethane	0.5	100	90	0.276	0.587	1.286
		10	99	0.285	0.749	1.465
		1	99.9	0.292	0.901	1.748
		0.1	99.99	0.297	1.054	2.322
	1	100	90	0.184	0.415	1.015
		10	99	0.190	0.568	1.177
		1	99.9	0.194	0.720	1.437
		0.1	99.99	0.197	0.871	2.980
	10	100	90	0.084	0.237	0.675
		10	99	0.087	0.368	0.820
		1	99.9	0.090	0.489	1.057
		0.1	99.99	0.094	0.603	1.566
1,1-Dichloro-ethylene	0.5	100	90	0.262	0.406	0.880
		10	99	0.265	0.448	0.963
		1	99.9	0.270	0.500	1.066
		0.1	99.99	0.272	0.531	1.243
	1	100	90	0.174	0.274	0.647
		10	99	0.177	0.307	0.721
		1	99.9	0.180	0.348	0.814
		0.1	99.99	0.181	0.371	0.977
	10	100	90	0.080	0.121	0.364
		10	99	0.081	0.144	0.423
		1	99.9	0.082	0.176	0.499
		0.1	99.99	0.083	0.196	0.640

[+]To convert from mgd to m^3/day, multiply by 3,785.
[†]To convert from $/1,000 gal to $/$m^3$, multiply by 0.26412

TABLE 4. PERFORMANCE SUMMARY FOR INORGANIC TECHNOLOGIES EXAMINED

Regulatory Phase	Inorganic Compound	Removal Efficiency			
		Reverse Osmosis	Ion Exchange	Aeration	Carbon Adsorption
II	Nitrate	++	++		
III	Radium	++	++		
III	Uranium	++	++		
III	Radon			*	*

++ = Excellent 70%-100%
* = Research being conducted by DWRD